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Hybrid Electric and Plug-in Hybrid Electric Vehicle Testing Activities

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Abstract

The Advanced Vehicle Testing Activity (AVTA) conducts hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) testing in order to provide benchmark data for technology modeling and research and development programs, and to be an independent source of test data for fleet managers and other early adaptors of advanced-technology vehicles. To date, the AVTA has completed baseline performance testing on 12 HEV models and accumulated 2.7 million fleet testing miles on 35 HEVs. The HEV baseline performance testing includes dynamometer and closed-track testing to document HEV performance in a controlled environment. During fleet testing, two of each HEV model accumulate 160,000 test miles within 36 months, during which maintenance and repair events and fuel use were recorded. Three models of PHEVs, from vehicle converters Energy CS and Hymotion and the original equipment manufacturer Renault, are currently in testing. The PHEV baseline performance testing includes 5 days of dynamometer testing with a minimum of 26 test drive cycles, including the Urban Dynamometer Driving Schedule, the Highway Fuel Economy Driving Schedule, and the US06 test cycle, in charge-depleting and charge-sustaining modes. The PHEV accelerated testing is conducted with dedicated drivers for 4,240 miles, over a series of 132 driving loops that range from 10 to 200 miles over various combinations of defined 10-mile urban and 10-mile highway loops, with 984 hours of vehicle charging. The AVTA is part of the U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program. These AVTA testing activities were conducted by the Idaho National Laboratory and Electric Transportation Applications, with dynamometer testing conducted at Argonne National Laboratory. This paper discusses the testing methods and results.

Keywords: plug-in, hybrid, electric, vehicle, testing

1. Introduction

The U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA) is conducting hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) testing to support AVTA's goal of providing benchmark data of emerging technologies for technology modeling and research and development programs conducted by DOE and its industry partners. The AVTA's testing results are also provided to fleet managers, who are often the early adapters of advanced vehicle technologies, and to the general public to support their vehicle acquisition processes.

There is significant interest in HEVs as an emerging technology; all automotive manufacturers are either currently offering HEVs or have made announcements about future HEV products. There is also significant interest in the development of PHEVs, which use larger batteries than "traditional" HEVs; the recharging of these PHEV batteries requires connecting (or plugging in) the vehicle to the offboard electric grid. PHEVs offer a greater pure electric vehicle (EV) range than conventional HEVs, a significantly greater electric assist than a comparable HEV, or combinations of both forms of additional electric-drive propulsion.

Depending on the operating scenario, compared to conventional internal combustion engine (ICE) vehicles, HEVs offer increased fuel efficiency or increased performance, or both, by combining the use of onboard traction battery packs and electric motors with ICEs. The PHEVs tested to date offer significantly higher fuel efficiencies than HEVs, with comparable vehicle performance, but also require PHEV users to recharge the batteries from an external source of electricity.

The AVTA uses two primary HEV test methods: (1) baseline performance testing is conducted on dynamometers and closed-test tracks, allowing for a highly controlled testing environment and vehicle-to-vehicle comparisons of test results; and (2) accelerated fleet testing places HEVs in commercial fleets where 160,000 miles of fuel use, repairs, maintenance, and life-cycle costs (including insurance and depreciation costs) are collected for each vehicle within 36 months. The accelerated testing provides a very real-world element to the testing process, but at an accelerated pace.

The PHEVs are also evaluated using baseline performance testing on dynamometers and closed-test tracks, but use a different type of accelerated testing. The PHEV accelerated testing is conducted on Phoenix, Arizona area streets and highways that have been combined into a 10-mile urban loop and a 10-mile highway loop. These two loops are used in combinations that result in drive cycles that range from 10 to 200 miles per drive, followed by battery recharging after every drive. These 132 repetitions of the 10 to 200-mile drive/battery recharge cycles are performed to collect electricity and gasoline use over 600 miles for each distance driven. This is defined in greater detail in the PHEV testing section (Section 3) of this paper.

The AVTA is part of DOE's FreedomCAR and Vehicle Technologies Program. These AVTA testing activities are conducted by the Idaho National Laboratory and AVTA's testing partner, Electric Transportation Applications, in Phoenix, Arizona. Argonne National Laboratory provides dynamometer testing for the AVTA.

2. Hybrid Electric Vehicle Baseline Performance Testing

2.1 Hybrid Electric Vehicle Baseline Performance Testing Methods

The HEV baseline performance testing is conducted according to AVTA's HEV Technical Specifications and 22 HEV testing procedures,[1] which cover the testing process from required minimum vehicle specifications through vehicle receipt, quality control, and test methods that measure vehicle performance (i.e., acceleration times, top speed, handling, braking, gradeability, fuel economy, and traction battery capacity at the end of testing). The SAE J1634 drive-cycle fuel economy tests, which include both the Urban Dynamometer Driving Schedule (UDDS; 1,372 seconds) and Highway Fuel Economy Driving Schedule (HWFEDS; 764 seconds), are conducted on a dynamometer in the following manner: two UDDS cycles, two HWFEDS cycles, a 10-minute rest, two additional UDDS, and two additional HWFEDS (i.e., UDDS, UDDS, HWFEDS, HWFEDS, 10-minute rest, UDDS, UDDS, HWFEDS, HWFEDS). The SAE J1634 dynamometer drive-cycle test is conducted twice, once with air conditioning off and one with the air conditioning on maximum.

To date, 12 HEV models have been baseline performance tested,[2] with various numbers of each model also being accelerated tested (Table 1).

Table 1. HEV models tested, the model year, the generation (Gen) if more than one generation of a model has been tested, the number of HEVs accelerated tested by model, and if the accelerated fleet testing is ongoing or completed. Unless noted, the vehicles are front wheel drive (A = all, WD = wheel drive).

HEV Model	Number Accelerated Tested	Accelerated Testing Status
2001 Honda Insight	6	Completed
2002 Gen I Toyota Prius	6	Completed
2003 Gen I Honda Civic	4	Completed
2004 Chevrolet Silverado (one 2 and one 4-WD)	2	Completing
2004 Gen II Toyota Prius	2	Completing
2005 Ford Escape (one front and one 4-WD)	2	Completing
2005 Honda Accord	2	Ongoing
2006 Lexus RX 400h (one front and two AWD)	3	Ongoing
2006 Toyota Highlander (AWD)	2	Ongoing
2006 Gen II Honda Civic	2	Ongoing
2007 Saturn Vue	2	Ongoing
2007 Toyota Camry	2	Ongoing
Total	35	

Note: When this paper was due, AVTA was acquiring two Nissan Altima HEVs.

2.1.1 Hybrid Electric Vehicle Performance Testing Results

Because of historical EV testing methods, accelerated testing of the first three HEVs (i.e., the Civic, Insight, and Gen I Prius) was conducted from 0 to 50 miles per hour (mph); the remaining eight HEV models were tested from 0 to 60 mph. All future HEVs will be tested from 0 to 60 mph.

The Accord had the fastest acceleration time (i.e., 8.5 seconds), followed closely by the Highlander and the RX400h (Figure 1).

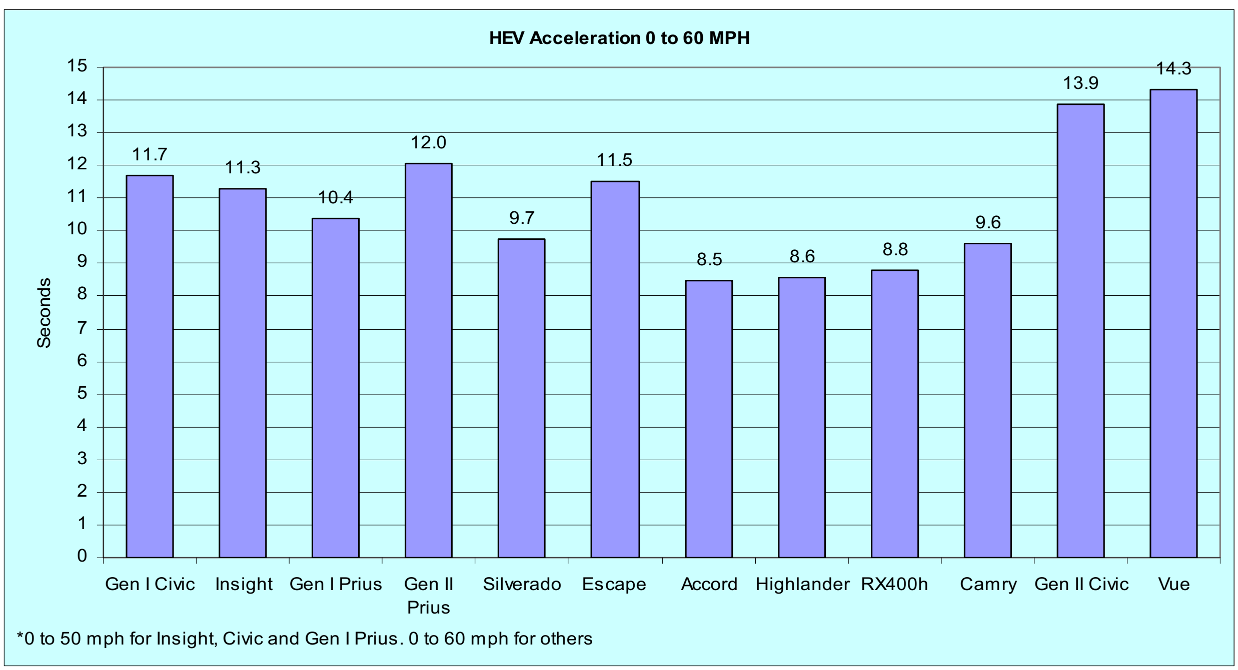

Figure 1. Results of HEV acceleration testing.

The maximum test speeds in the quarter mile ranged from 68 mph for the Gen I Civic to 87 mph for the Accord, and the maximum calculated speed on a 6% grade ranged from 72 mph for the Insight to 110 mph for the Camry (Figure 2). The braking distances ranged from 129 feet for the Gen II Civic to 172 feet for the heavier Silverado during the controlled, dry braking test (Figure 3).

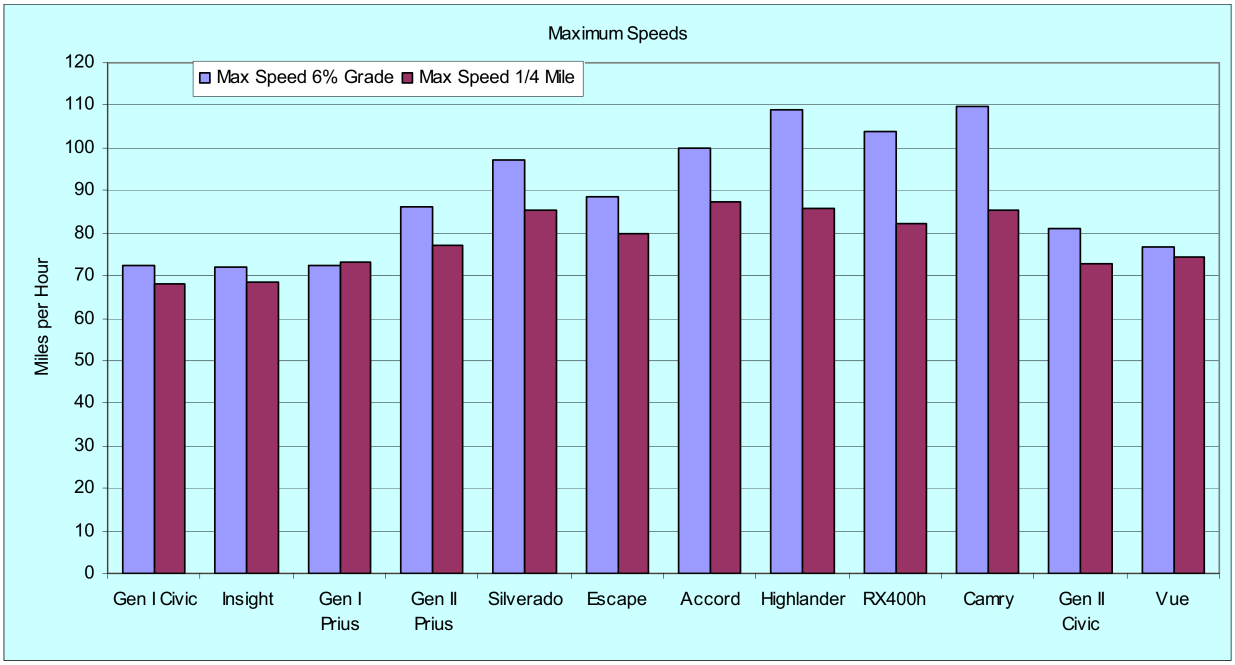

Figure 2. Test results for the HEV maximum speed track test in a quarter mile and for the calculated HEV maximum speed on a 6% grade.

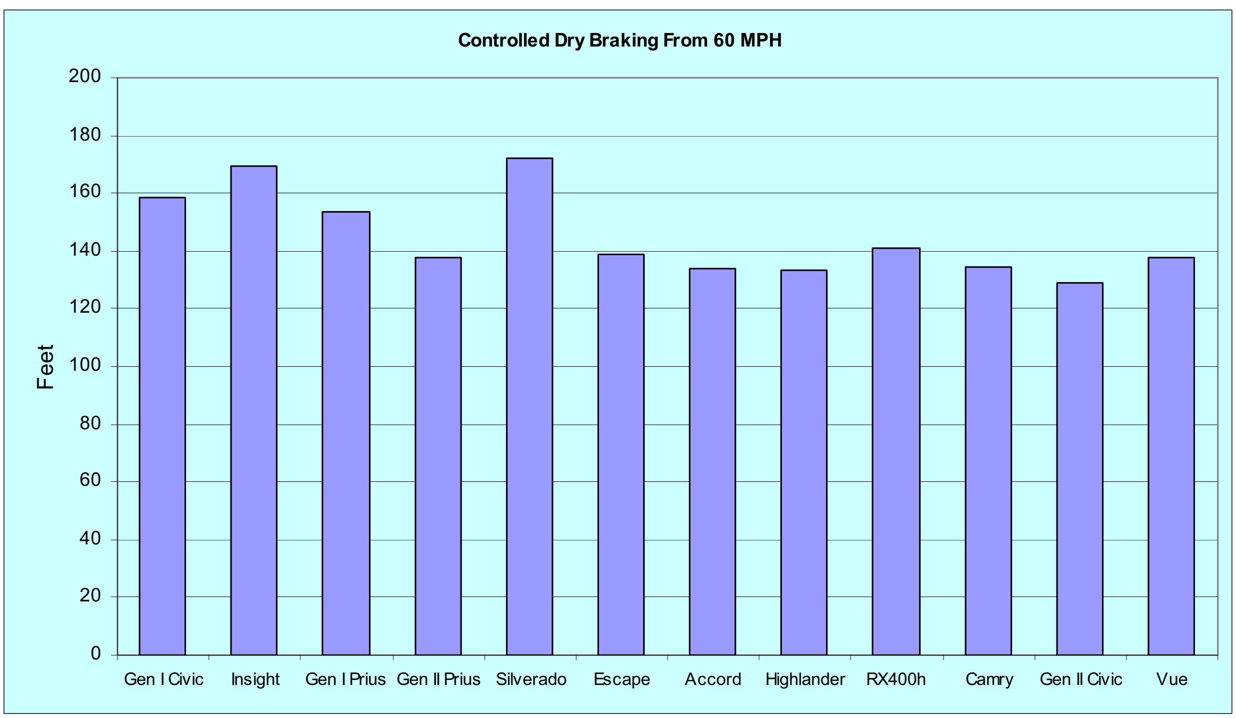

Figure 3. HEV test results for controlled dry braking from 60 mph.

2.1.2 Results for Hybrid Electric Vehicle Dynamometer Fuel Economy Testing

One of each HEV model was dynamometer tested with the air conditioning off and again with the air conditioning on maximum. Test results with the air conditioning off ranged from 18.8 miles per gallon (mpg) for the Silverado to 56.2 mpg for the Insight (Figure 4). The average was 40.4 mpg for HEVs with the air conditioning off during testing. When the identical dynamometer tests were conducted with the air conditioning on maximum, results ranged from 16.0 mpg for the Silverado to 42.7 mpg for the Insight (Figure 4). The average fuel economy with air conditioning on maximum was 31.3 mpg.

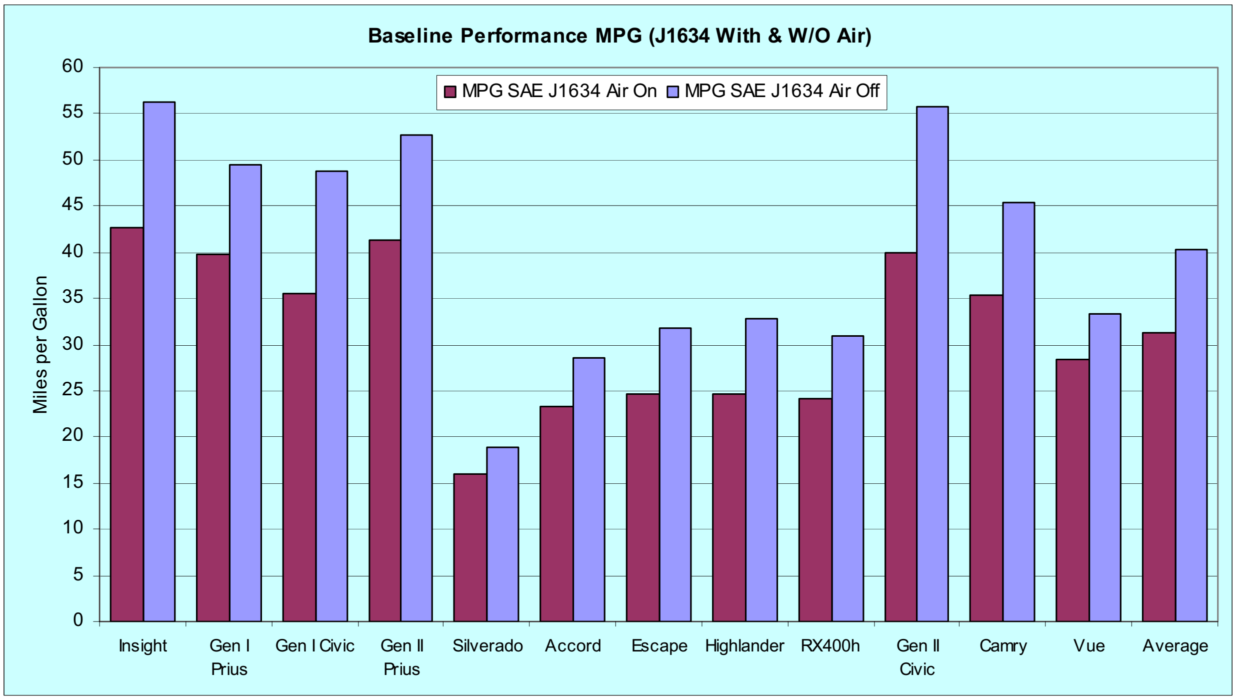

Figure 4. Dynamometer fuel economy test results with air conditioning off and on.

Fuel economy decreases due to use of air conditioning during the dynamometer tests were recorded for all HEVs. In pure numbers, the largest mpg decrease recorded was 15.8 mpg for the Gen II Civic, and the smallest decrease recorded was 2.8 mpg for the Silverado. The Gen II Civic had the highest percentage mpg decrease (i.e., 28.4%) when the air conditioning was on (Figure 5), and the Vue had the lowest mpg percentage decrease (i.e., 14.6%). The average decrease in mpg due to use of air conditioning during the dynamometer test was 22.4%.

2.1.3 Hybrid Electric Vehicle Battery Discharge During Dynamometer Testing

When dynamometer tests were conducted with and without the air conditioning on, traction battery throughput (Ah) was collected for each HEV. This data is presented in Figure 6, normalized to nominal battery capacity, such that 1C represents a capacity throughput equal to the nominal rated capacity of the HEV battery.

Test results ranged from 0.72C for the Silverado dynamometer test with the air conditioning off to 3.38C for the Gen II Prius with the air conditioning on. The average normalized throughput for the test with air conditioning on was 1.83C and with the air conditioning off it was 1.64C.

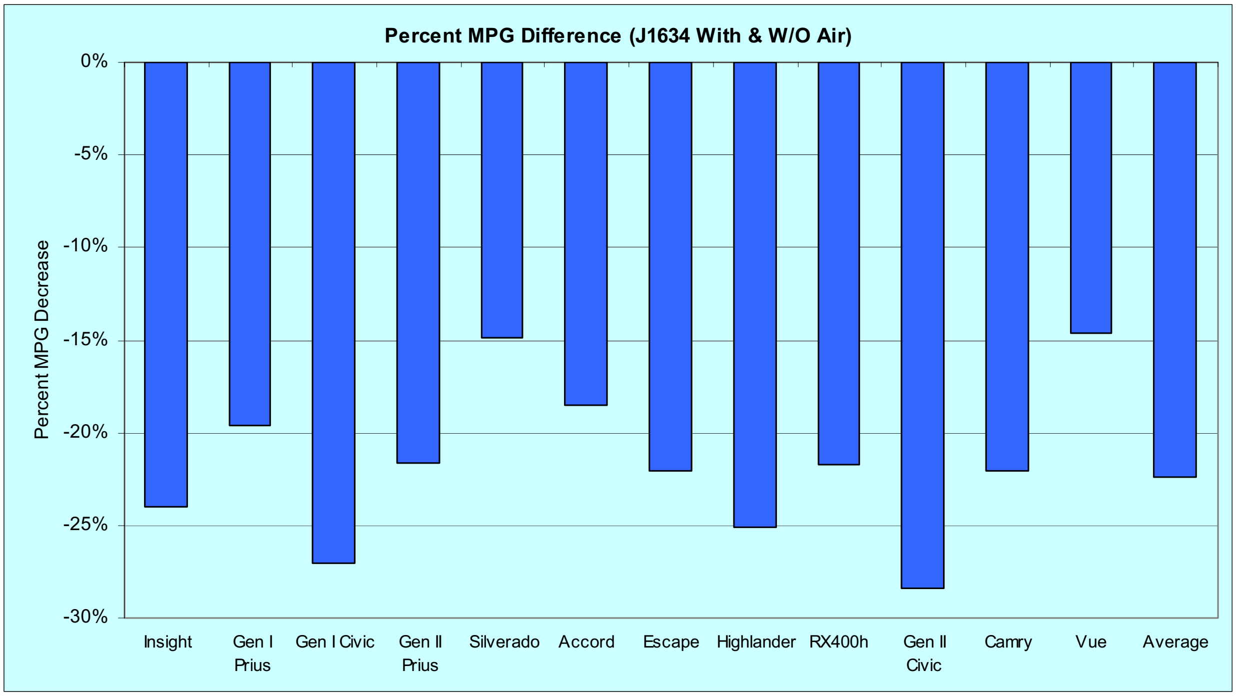

Figure 5. Percentage decrease in HEV mpg during the dynamometer test when the air conditioning is turned on maximum compared to the air conditioning off.

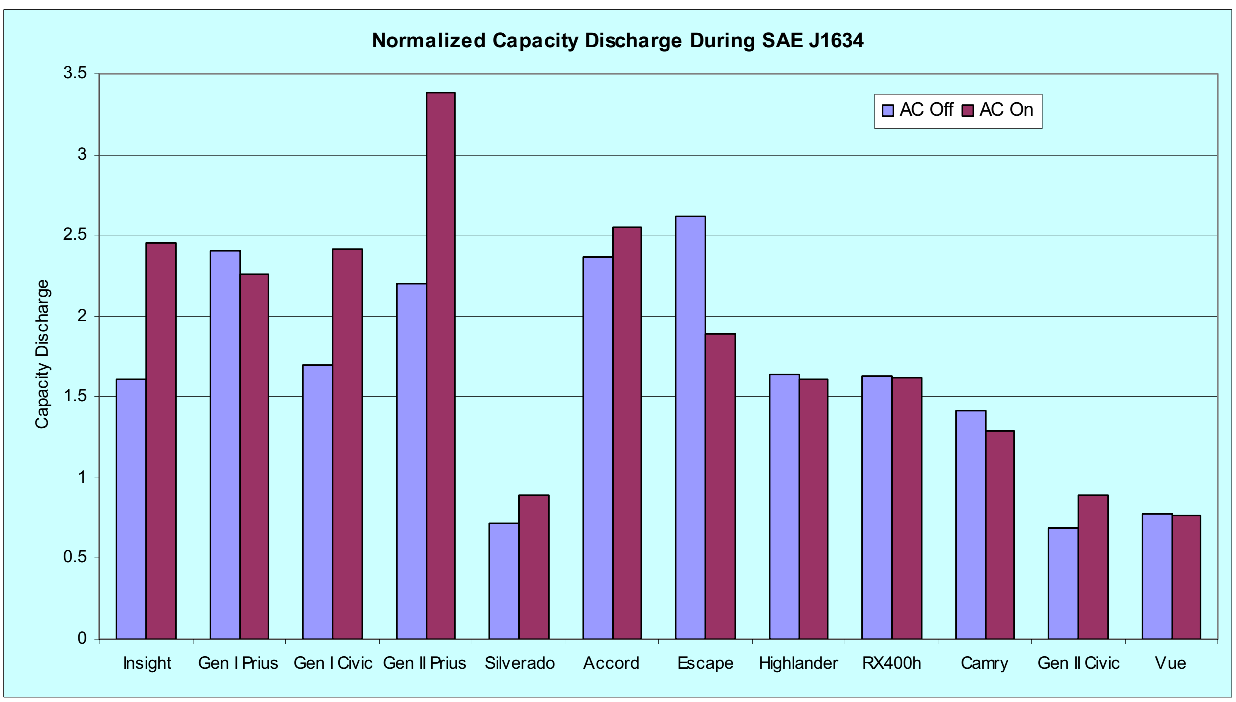

Figure 6. Capacity discharged from HEV traction batteries during dynamometer tests with the air conditioning on and with the air conditioning off.

2.2 Hybrid Electric Vehicle Fleet Testing

2.2.1 Fleet Testing Background and Methods

Originally, fleet testing consisted of two categories: (1) "regular" fleet testing, with no attempt to maximize mileage accumulation, and (2) accelerated testing, with maximum effort to collect many miles in short periods of time. Prior to HEV testing, fleet testing of pure EVs usually meant accumulating 12,000 miles per test vehicle within 12 months. Only with dedicated drivers, and at times, significant exertion could additional mileage be accumulated on pure EVs. For instance, operating a pure EV more than one discharge cycle per day required almost 24 hours per day of testing.

The introduction and operating capabilities of HEVs allowed the AVTA to place them in fleets that accumulate high mileages in abbreviated timeframes as part of normal operations. For HEVs, 160,000 test miles are accumulated per test vehicle in 36 months, on two of each HEV model tested. The benefits of accelerated mileage accumulation include the accelerated accumulation of data; therefore, vehicle engineers, modelers, and fleet managers receive timely and meaningful life-cycle results.

Some of the early HEVs were only fleet tested for less than 25,000 miles; however, test results for these lower mileage HEVs and the 160,000-mile HEVs are discussed together in this paper. "Fleet testing" refers to both groups of vehicles. Fleet testing methods are based on AVTA's Fleet Test and Evaluation Procedure.[3] The HEVs are operated in several fleets in the greater Phoenix, Arizona area, including some use in Flagstaff, Arizona. The HEVs that accumulate 160,000 miles in 36 months are operated solely by JPMorgan's fleet.

To date, the 35 HEVs that have entered fleet testing have accumulated over 2.7 million test miles (Figure 7).

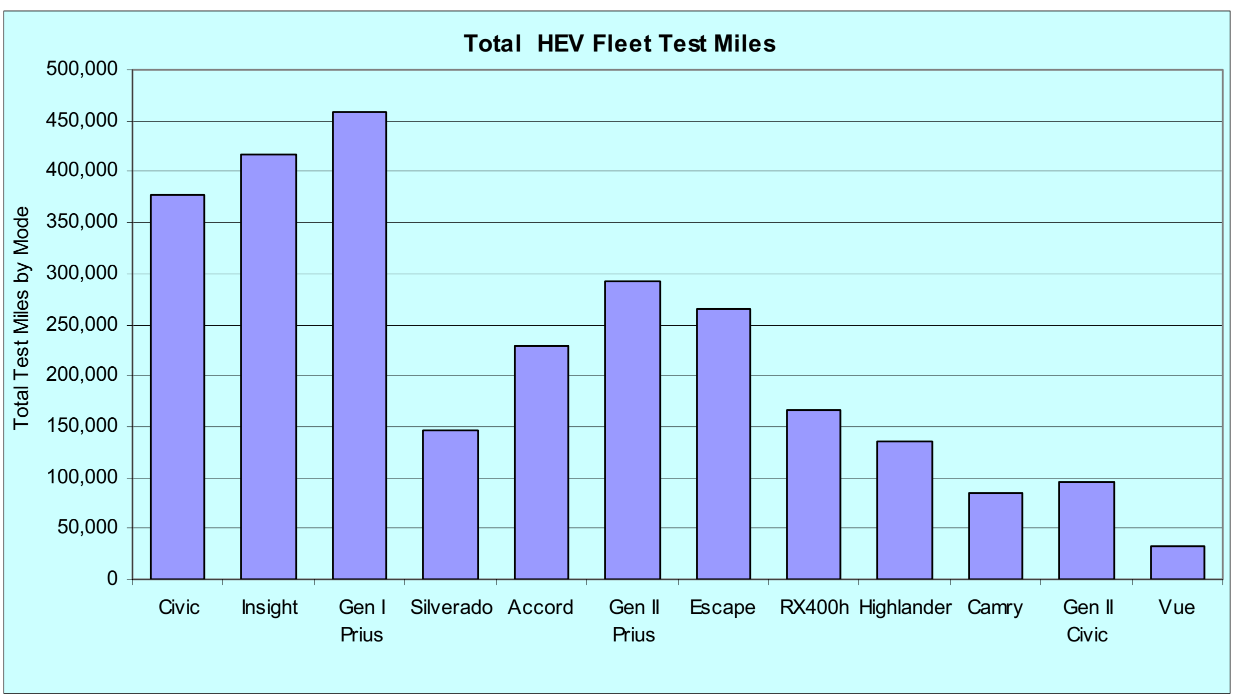

Figure 7. HEV fleet test mileage accumulation by HEV model.

2.2.2 Fleet Testing Fuel Efficiencies

Fuel efficiencies for HEVs in the fleet testing range from 17.8 mpg for the Silverado HEVs (i.e., 17.8 mpg for the 4WD and 17.7 for the 2WD) to 44.2 mpg for the Gen II Prius and 45.2 mpg for the retired Insight (Figure 8). Clear seasonal variation in mpg existed for the early HEVs (i.e., Insight, Gen I Civic, and Gen I Prius) when viewed on a month-to-month basis (Figure 9), with mpg highest during the cool months and lowest during the warm months when air conditioning use is highest. The more recent HEV models, with their more powerful engines, have less seasonal variations. Minor month-to-month variations can be attributed to test miles being accumulated during one month, with a fueling event occurring at the very being of the next month.

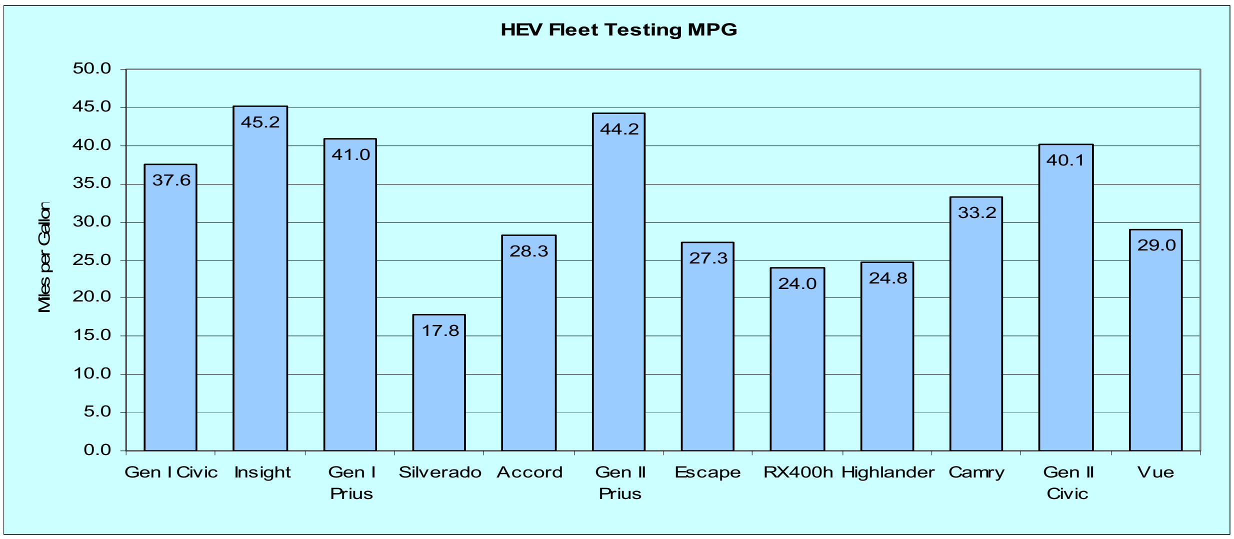

Figure 8. Accelerated fleet testing mpg results for HEVs.

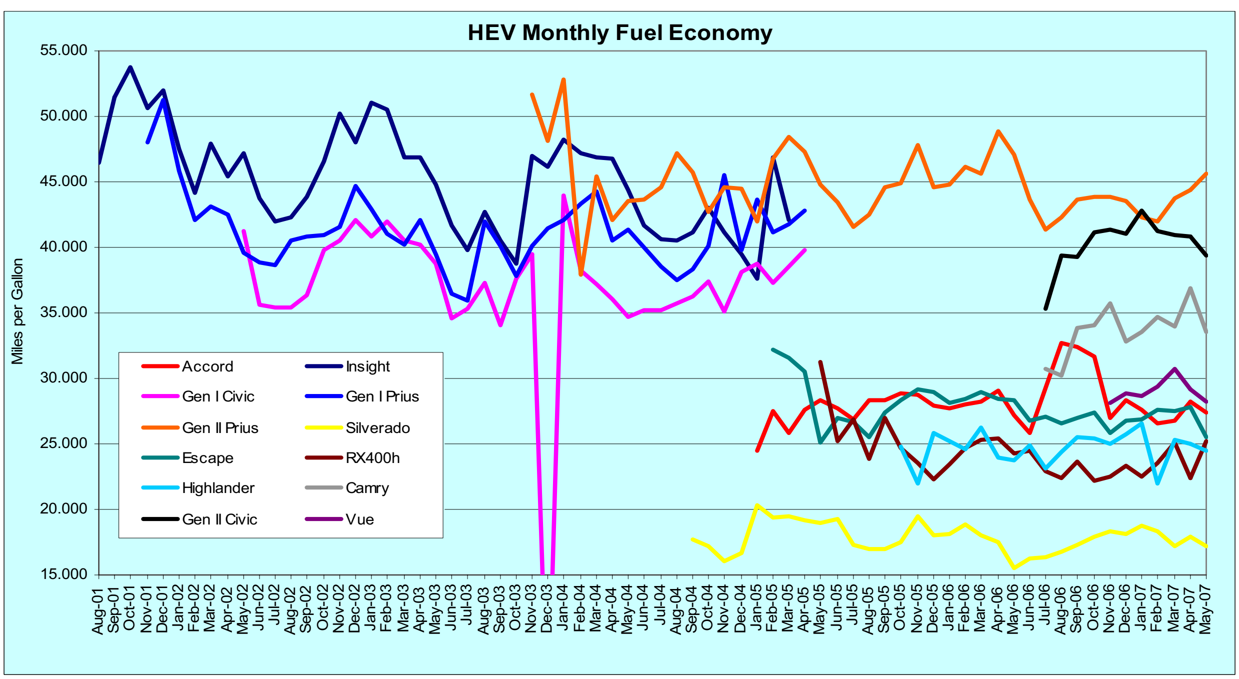

Figure 9. Monthly mpg results for all of the HEVs tested. Note that the Honda Civic data for December 2004 was very low because both vehicles were in repair and fueling events occurred; however, few miles were accumulated.

2.2.3 Hybrid ElectricVehicle Fleet Testing Maintenance and Repair Requirements

Maintenance and repair requirements for HEVs are tracked and reported on a per-vehicle basis. Data collected and disseminated include the date of the repair or maintenance event, any action taken (e.g., oil changes to battery pack replacement), the miles on the vehicle when the event occurred, and the cost (or if under warranty) per repair or maintenance event. A sample of a single page of a Highlander maintenance sheet can be seen below (Figure 10). For additional maintenance sheets, see AVTA's HEV webpages at http://avt.inel.gov/phev.shtml.

FREEDOMCAR & VEHICLE TECHNOLOGIES PROGRAM

HEV Fleet Testing

Advanced Vehicle Testing Activities

Maintenance Sheet for 2006 – Highlander

FreedomCAR & Fuel Partnership

VIN # JTEDW21A160006395

Date	Mileage	Description	Cost
12/14/2005	4,855	Changed oil, rotated tires	$31.99
1/5/2006	9,952	Changed oil, rotated tires	$28.04
1/31/2006	15,749	15K service	$187.05
2/22/2006	20,783	Changed oil, rotated tires	$28.07
3/15/2006	26,197	Changed oil, rotated tires	$28.10
4/17/2006	31,578	30K service	$321.80
4/26/2006	36,682	Changed oil, rotated tires	$28.99
5/18/2006	42,113	Changed oil, rotated tires	$28.99
6/9/2006	47,475	15K interval service, 45K preventative maintenance	$200.67
7/5/2006	53,711	Changed oil	$38.44
7/26/2006	59,632	60K service	$346.86
8/21/2006	65,947	Changed oil	$38.31
9/12/2006	71,030	Changed oil, replaced wiper blades	$57.20
9/14/2006	71,053	Check engine light on - Code PA93 Inverter cooling system malfunction inverter coolant low	warranty
9/29/2006	73,015	Replaced windshield	$272.87
10/6/2006	75,949	75K service	$200.67
12/6/2006	90,270	Changed oil	$39.60

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Figure 10. One page of the Highlander maintenance sheet.

2.3 Comparing Advanced Vehicle Testing Activity and Environmental Protection Agency Hybrid Electric Vehicle Fuel Economy Test Results

The Environmental Protection Agency (EPA) has announced and implemented new test methods (http://www.fueleconomy.gov/feg/ratings2008.shtml) for estimating mpg ratings for all light-duty vehicles. Figure 11 shows both the original EPA mpg estimates (light yellow bars) for HEVs the AVTA has tested, and mpg figures the EPA has published if the same vehicles were tested, or calculated to have been tested, to the new test methods (blue bars). The EPA numbers are displayed as the average for both city and highway results. Results for the AVTA fleet testing also are graphed (red bars) to show comparison to the old and new EPA estimates. The HEVs are displayed by all-wheel, two-wheel, and four-wheel drive in order to match EPA test categories. Note that the average AVTA fleet testing mpg is 31.0 mpg, which is close to the new EPA test method average of 31.7 mpg (2.2% higher than results for the AVTA fleet testing). The older EPA test method results averaged 36.6 mpg (18.1% higher than results for the AVTA fleet testing).

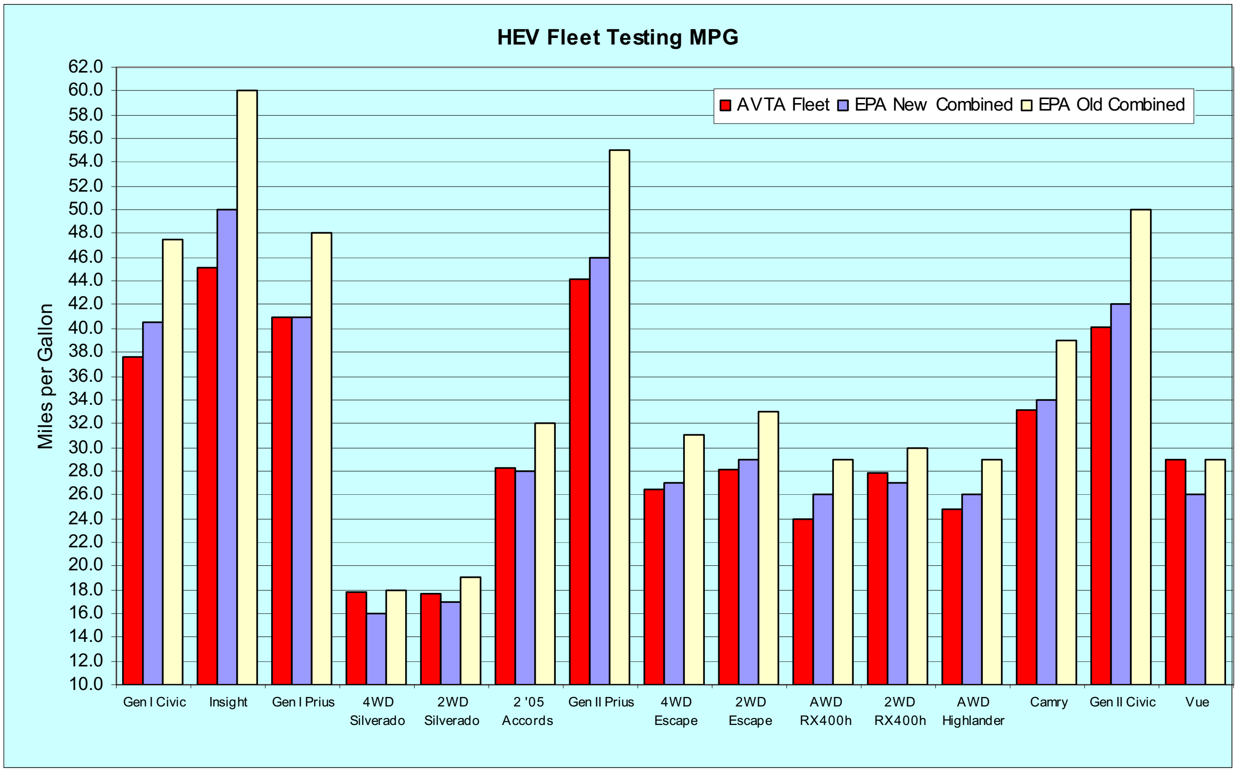

Figure 11. Results for the AVTA fleet testing compared to the results for the old and new EPA mpg testing. The 12 HEV models are broken out into two-wheel, four-wheel, and all-wheel drive categories to match EPA vehicle categories.

3. Plug-in Hybrid Electric Vehicle Baseline Performance Testing

3.1 Plug-in Hybrid Electric Vehicle Baseline Performance Testing Methods

Baseline performance testing is conducted according to the AVTA's PHEV Integrated Test Plan and Evaluation Program,[4] which covers the testing process from the required minimum vehicle specifications to vehicle receipt, quality control, and testing methods, which measure vehicle performance (i.e., acceleration times, top speed, handling, braking, gradeability, fuel use, and traction battery capacity at the end of testing). The PHEV baseline performance testing is also conducted on closed test tracks and dynamometers, which allows very repeatable testing in the following areas:

- Fuel consumption (both gasoline and electricity)
- Acceleration
- Gradeability
- Road load coefficients (to support dynamometer testing)
- Vehicle durability
- Charger performance.

Dynamometer testing is conducted in each vehicle's Normal Operation mode (the mode most appropriate for fleet operations). When all-electric operation is possible (Rechargeable Energy Storage System Only mode), testing is conducted beginning at 100% state-of-charge and 50% state-of-charge. The AVTA's drive-cycle dynamometer test includes UDDS and the HWFEDS. Track testing is conducted at automotive proving grounds near Phoenix, Arizona. Dynamometer testing is conducted at Argonne

National Laboratory's Advanced Powertrain Test Facility outside Chicago, Illinois. Test results are presented in test reports and summarized for wide dissemination in one-page data sheets.[5]

The dynamometer portion of the baseline performance testing is conducted over a 5-day period and includes a minimum of 26 drive-cycle tests, in both charge depleting and charge sustaining test cycles (similar to how the PHEVs will likely be operated), both with air conditioning on and off.

To date, three PHEV models have been baseline performance tested, and the configurations are listed below:

- Energy CS
  - Base vehicle—Toyota Prius
  - Removes original Prius battery pack
  - Uses Valance 9-kWh lithium pack
  - Parallel hybrid configuration
- Hymotion
  - Base vehicle—Toyota Prius
  - Prius battery pack remains
  - Uses A123Systems 5-kWh lithium battery pack
  - Parallel hybrid configuration
- Renault Kangoo
  - Original equipment manufacturer vehicle
  - Saft 9.6-kWh (measured) NiCad battery pack
  - Series hybrid configuration.

3.1.1 Energy CS and Hymotion Plug-in Hybrid Electric Vehicle Energy Use During Dynamometer Testing

The Energy CS and Hymotion PHEV conversions were both UDDS and HWFEDS tested in the charge-depleting mode until they went into charge-sustaining modes; testing was then continued for two additional charge-sustaining cycles. The graphs in this section repeat the charge-sustaining mode results in order to highlight cumulative gasoline and cumulative electricity use as driving distance increases. The bars show respective mpg test results for each UDDS and HWFEDS test cycle, while the lines in each graph show cumulative mpg and electricity use.

During UDDS testing, the Energy CS Prius PHEV had greater than 100 mpg during the first four test cycles (Figure 12). The cumulative fuel economy was over 100 mpg after nine UDDS cycles (67 miles), and the total cumulative electricity use was 5.6 kWh during this testing. Note that the kWh discussed in this section is the kWh alternating current (AC) that the vehicle operator will be required to purchase for recharging the vehicles.

During HWFEDS testing, the Energy CS Prius conversion exhibited (Figure 13) over 100 mpg test results for the first two test cycles (about 20 miles), with a cumulative fuel economy over 80 mpg after seven test cycles (about 72 miles). A total of 5.9 kWh was consumed during this testing.

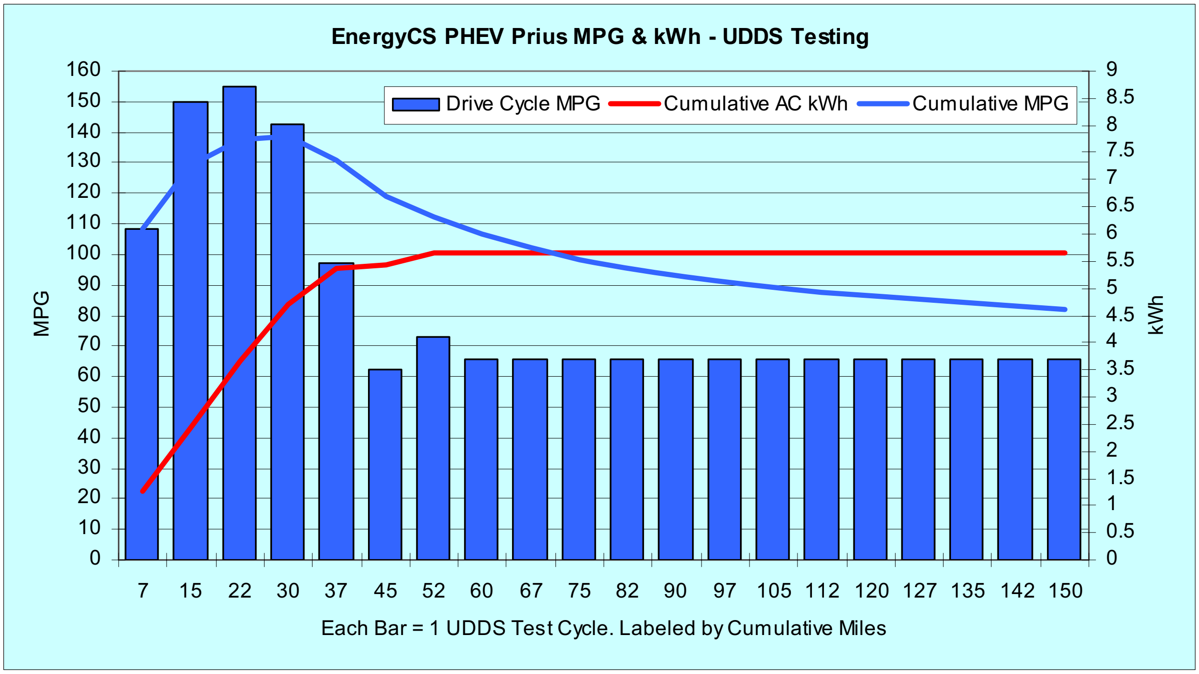

Figure 12. UDDS test results for the Energy CS Prius conversion test vehicle.

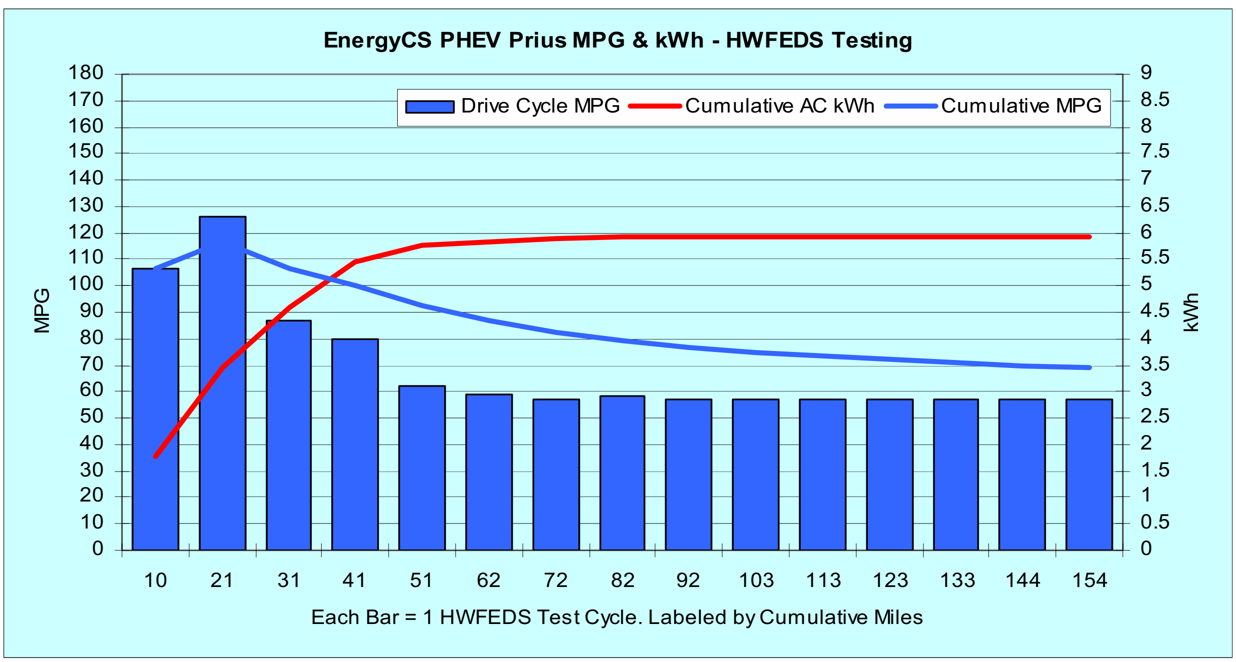

Figure 13. HWFEDS test results for the Energy CS Prius conversion test vehicle.

Figure 14 shows electricity and gasoline costs per mile to operate the Energy CS conversion, based on results of the UDDS and HWFEDS tests. Costs are based on a gasoline cost of $3.25 per gallon and an electricity cost of $0.10 per kWh. The solid blue and red lines show total cost per mile for fuel (both electricity and gasoline). As the vehicle is operated greater distances over the test cycles, the fuel cost per mile increases as the fuel mix changes to more gasoline use per mile and less electricity use per mile.

During UDDS testing, the Hymotion PHEV conversion exhibited fuel economy results over 145 mpg during the first two test cycles, and over 170 mpg during the third cycle (Figure 15). The cumulative fuel economy was over 100 mpg after seven UDDS cycles (52 miles), and the total cumulative electricity use was 3.6 kWh during this testing.

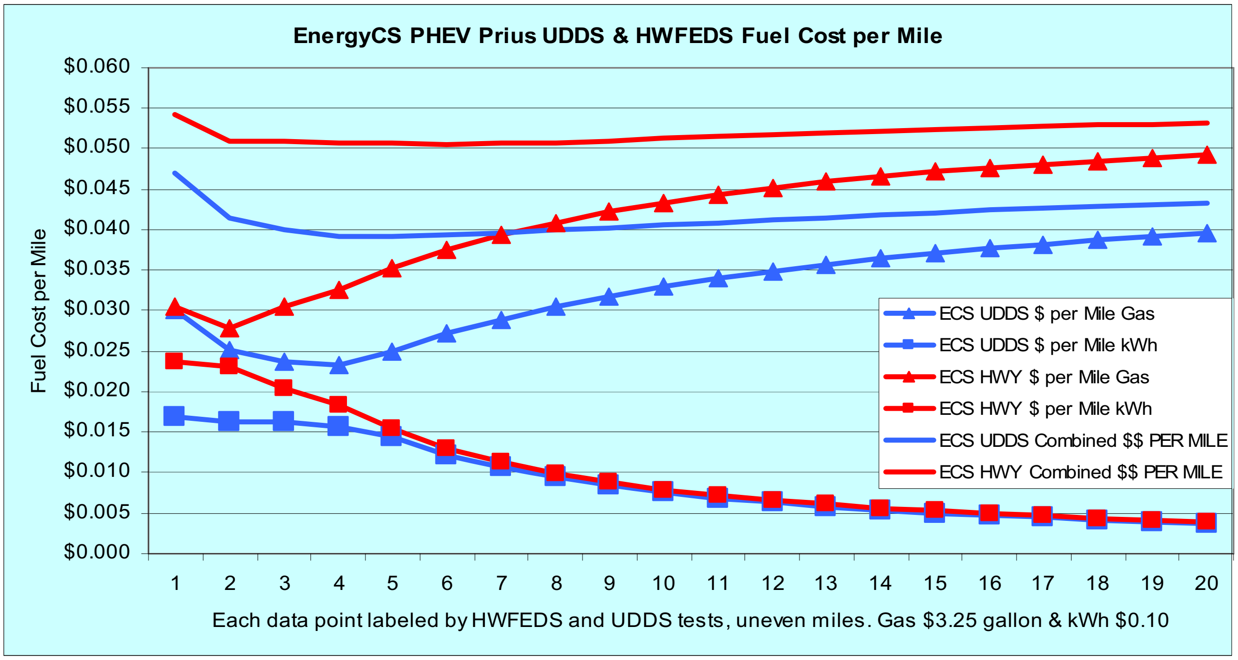

Figure 14. Gasoline and electricity cost per mile by UDDS and HWFEDS (HWY used in graph) test for the Energy CS PHEV.

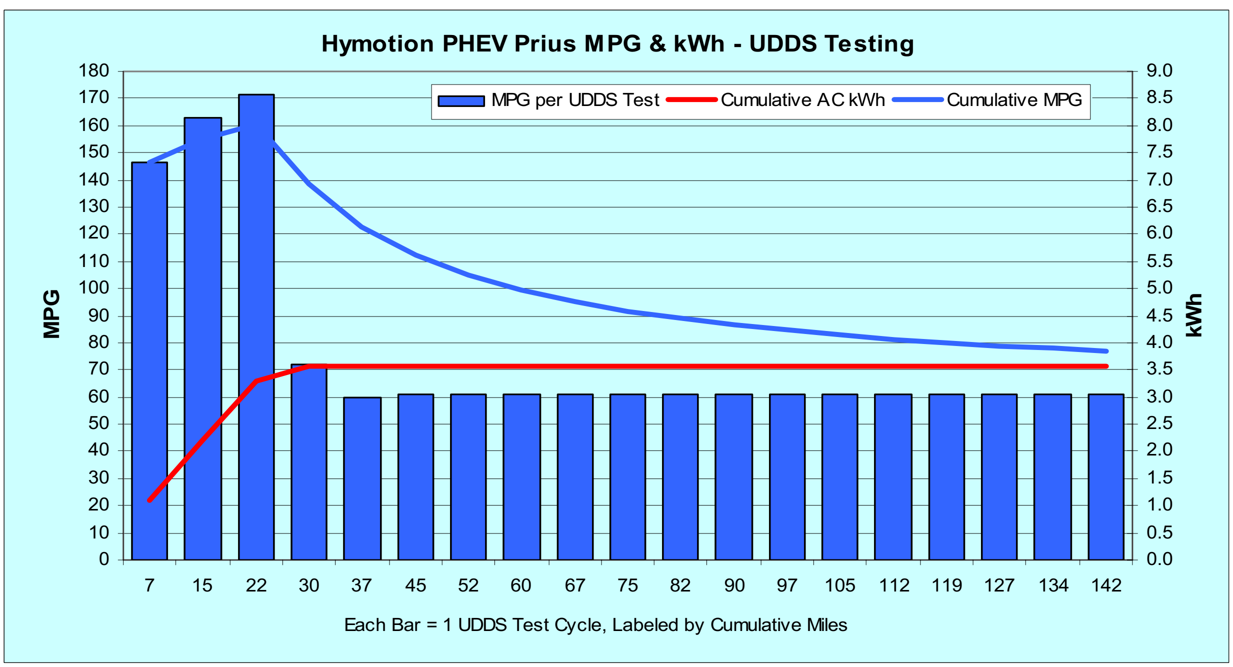

Figure 15. UDDS test results for the Hymotion CS PHEV.

During HWFEDS drive-cycle testing, the Hymotion PHEV conversion exhibited over 87-mpg test results for the first three test cycles (about 31 miles), with cumulative fuel economy over 79.8 mpg after five test cycles (about 51 miles). A total of 3.9 kWh AC was consumed during this testing (Figure 16).

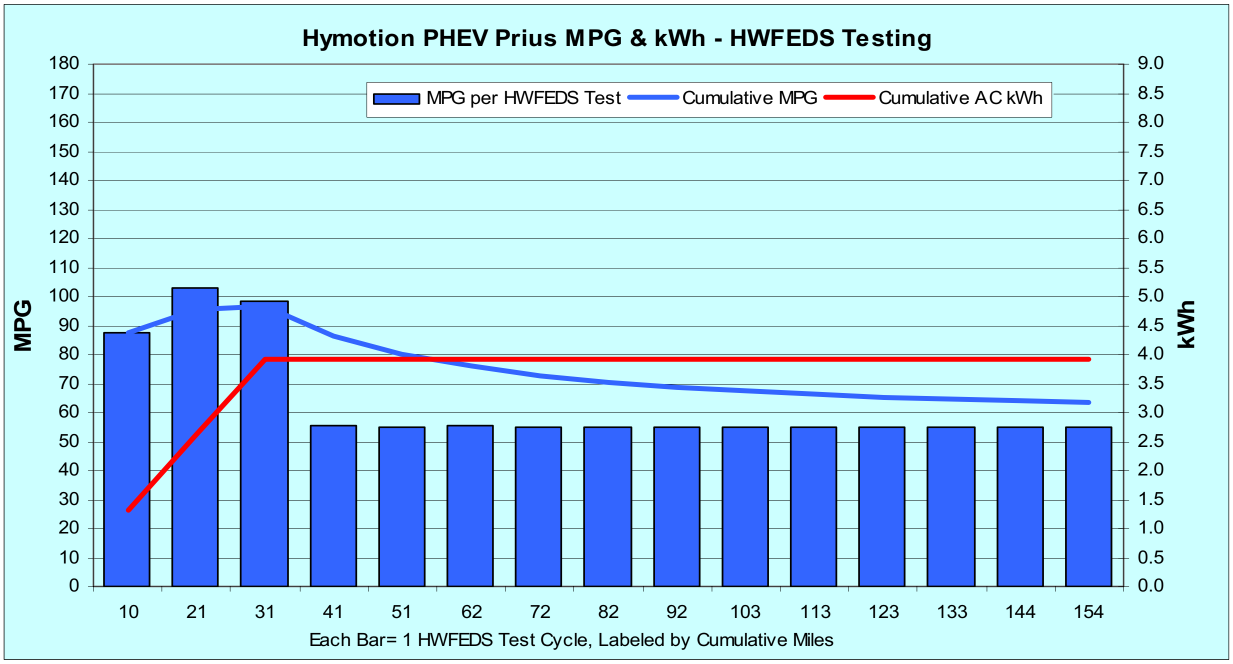

Figure 16. HWFEDS test results for the Hymotion Prius conversion test vehicle.

Figure 17 shows electricity and gasoline costs per mile to operate the Hymotion PHEV conversion, based on results of the UDDS and HWFEDS tests. Costs are based on a per-gallon gasoline cost of $3.25 and an electricity cost of $0.10 per kWh. The solid blue and red lines show total cost per mile for fuel (both electricity and gasoline). As the vehicle is operated greater distances over the test cycles, the fuel cost per mile increases as the fuel mix changes to more gasoline use per mile and less electricity use per mile.

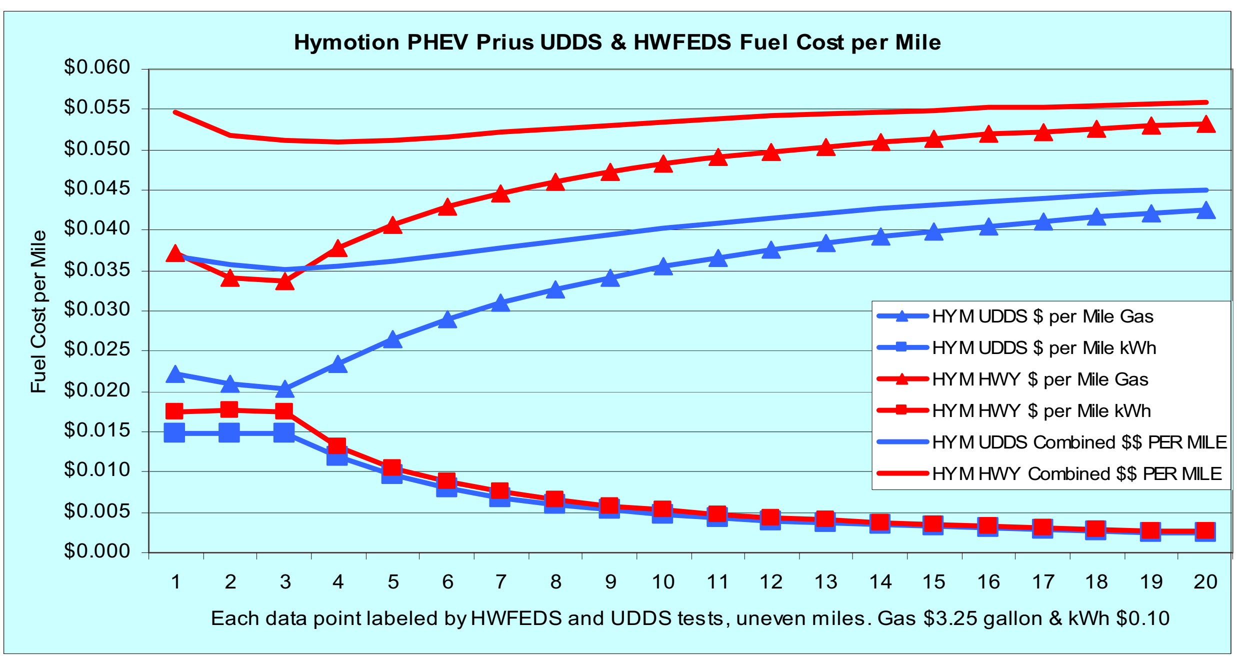

Figure 17. Hymotion PHEV gasoline and electricity cost per mile by UDDS and HWFEDS tests (HWY used in this graph).

3.1.2 Kangoo Plug-in Hybrid Electric Vehicle Energy Use During Baseline Performance Testing

The Kangoo (Figure 18) uses its 650-cc ICE, which can be turned on and off by the operator, more as a range extender for the battery pack; the Toyota ICE in the Hymotion and Energy CS PHEV conversions turns on and off without driver input.

Figure 18. Renault Kangoo PHEV.

Because of the unique operating characteristics of the Kangoo, it was tested differently than other PHEVs tested to date. Baseline performance test results presented in Table 2 show how the Kangoo was tested both in electric drive only mode and with the gasoline engine turned on. As seen in this table, the Kangoo’s mpg test results are significantly lower than those for the Hymotion and Energy CS PHEVs. Figure 19 shows the cost per mile to operate the Kangoo in several different operating modes.

Table 2. Kangoo baseline performance energy use.

Test Cycle	kWh AC per Mile	Miles per Gallon
Battery only—UDDS	0.268	
Battery only—HWFEDS	0.155	
Battery only at constant 45 mph	0.271	
Battery and ICE cold start UDDS	0.144	42.3
Battery and ICE hot start UDDS	0.110	39.4
Battery and ICE hot start HWFEDS	0.481	40.9

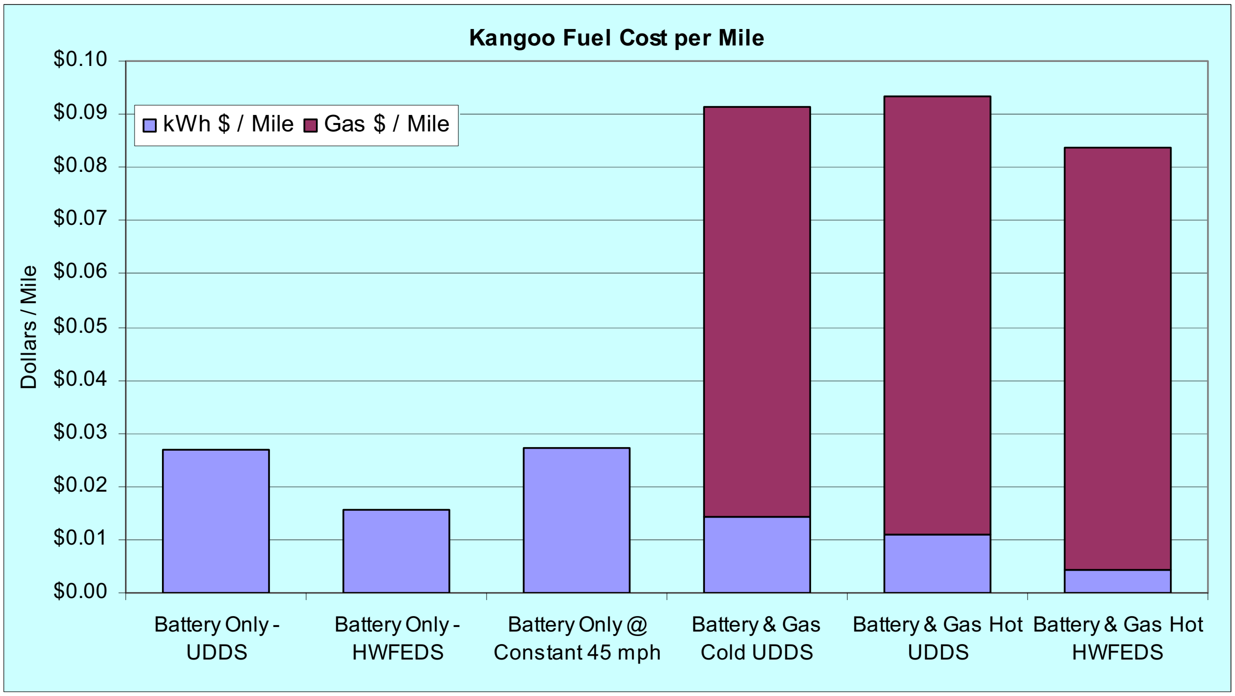

Figure 19. Fuel cost per mile to operate the Kangoo PHEV (a gasoline fuel cost of $3.25 per gallon is assumed and a kWh cost of $0.10 is assumed).

3.2 Plug-in Hybrid Electric Vehicle Accelerated Testing

Accelerated testing rapidly provides performance and reliability data for PHEVs by using dedicated drivers to drive PHEVs on fixed routes in and around Phoenix, Arizona. This allows for accelerated accumulation of fuel-use data for trips of defined lengths. The PHEV trips are organized as shown in Table 3. All repetitions for each cycle are run before starting another test cycle. This allows for gasoline use to be measured only once after completing the entire 200, 600, or 640 miles of each cycle. For instance, the 60-mile drive cycle is driven, the test vehicle is charged at least 12 hours, and all 10 repetitions are conducted, after which gasoline use is measured. Electricity use is recorded after each charging event.

Table 3. PHEV accelerated testing methods.

Cycle (mi)	Urban (10 mi)	Highway (10 mi)	Charge (hours)	Repetitions (N)	Total (mi)	Repetitions (%)	Miles (%)	Cumulative (mi)
10	1	0	4	60	600	45%	14%	600
20	1	1	8	30	600	23%	14%	1,200
40	4	0	12	5	200	4%	5%	1,400
40	2	2	12	5	200	4%	5%	1,600
40	0	4	12	5	200	4%	5%	1,800
60	2	4	12	10	600	8%	14%	2,400
80	2	6	12	8	640	6%	15%	3,040
100	2	8	12	6	600	5%	14%	3,640
200	2	18	12	3	600	2%	14%	4,240
Total	1,740	2,500	984	132	4,240			4,240
Average	41%	59%	7.5	32.1				

Only the Energy CS PHEV has completed most of the accelerated testing to date, and as can be seen in Table 4, it has not yet completed the 10-mile or 20-mile tests. As shown in Table 4, this vehicle's highest mpg results occur when driven a higher percentage of time on urban versus highway loops.

Table 4. Energy CS PHEV accelerated testing results to date.

Cycle (miles)	Urban (10-mile)	Highway (10-mile)	Charge (hours)	Reps (number)	Total (miles)	Electricity (kWh)	Gasoline	
							(gallons)	(mpg)
10	1	0	4	60	600			
20	1	1	8	30	600			
40	4	0	12	5	200	17.37	1.61	124.2
40	2	2	12	5	200	29.00	1.42	140.8
40	0	4	12	5	200	30.00	2.43	82.3
60	2	4	12	10	600	65.00	5.90	101.7
80	2	6	12	8	640	39.04	10.09	63.4
100	2	8	12	6	600	22.67	8.81	68.1
200	2	18	12	3	600	12.98	10.46	57.4

3.3 Plug-in Hybrid Electric Vehicle and Non-Plug-in Hybrid Electric Vehicle Fuel Costs per Mile

To put fuel costs for PHEVs in perspective, Figure 20 shows the combined electricity and gasoline fuel cost per mile for UDDS and HWFEDS (HWY) testing of the Energy CS (ECS) and Hymotion (HYM) Prius conversions. Figure 20 also shows fuel costs for the Energy CS (ECS) Prius accelerated testing results to date, for a conventional HEV Toyota Prius that gets 45 mpg, and for conventional non-HEV ICE vehicles that get 20 and 30 mpg.

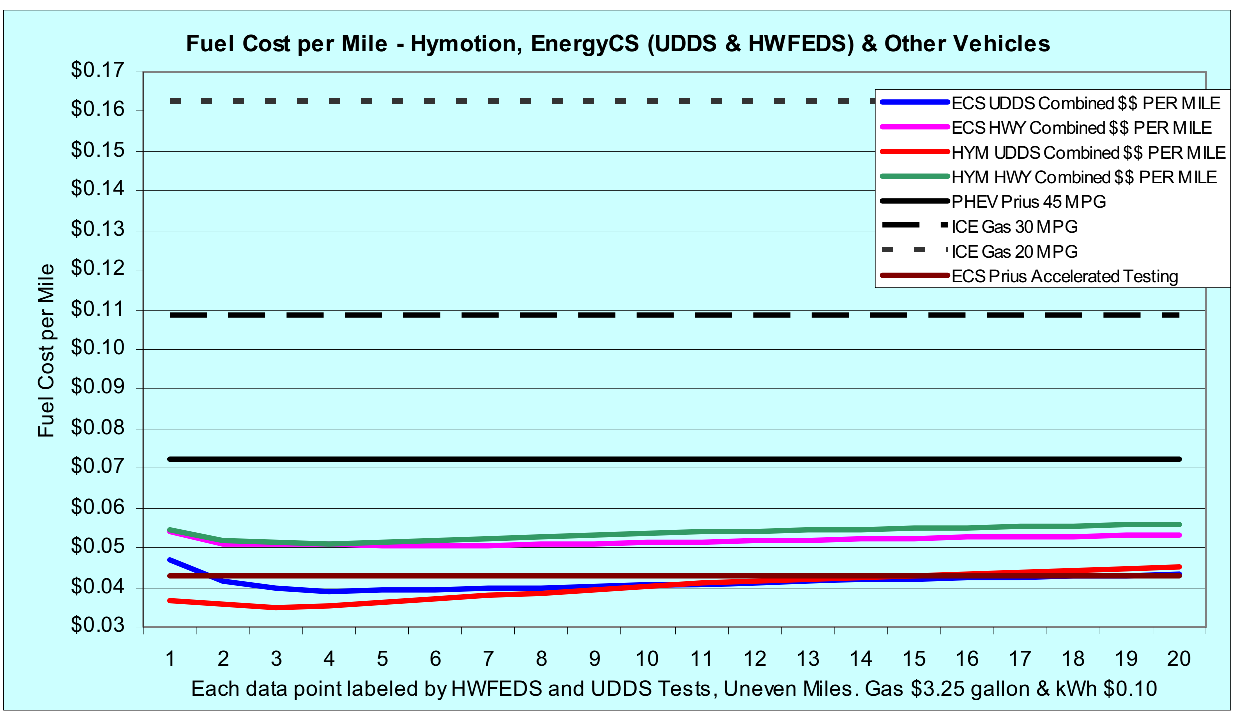

Figure 20. Fuel cost per mile for PHEVs, an HEV, and ICE vehicles at 20 and 30 mpg.

As shown in Figure 20, the combined electricity and gasoline costs per mile for PHEVs range from about 3.5 to about 5.5 cents per mile, with the lowest costs occurring when more electricity is proportionally being used to propel the test vehicles. Comparatively, the HEV Toyota Prius, with no offboard electricity charging, costs 7 cents per mile, and the ICE vehicles average 11 and 16 cents per mile. Costs of $3.25 per gallon of gasoline and $0.10 per kWh of electricity were assumed.

3.4 Future Testing of Plug-in Hybrid Electric Vehicles

In a partnership with the New York State Energy Research and Development Agency (NYSERDA), the AVTA will be testing the following PHEVs conversions in the near term: Hymotion Civic, Hymotion Escape, HybridsPlus Escape, and an Electrovaya Escape. All of these PHEVs have lithium traction battery packs. It is anticipated that all of these vehicles will be delivered for testing by the end of September 2007, with the Electrovaya Escape delivered in August 2007. These vehicles will undergo both baseline performance testing and accelerated testing.

Small demonstration fleets for PHEVs also are being developed between the AVTA and various fleets. Some of these locations include, or are likely to include, New York State, Seattle and Tacoma in Washington State, and several fleets in California and Hawaii. In addition, cooperative testing is being conducted with some of the PHEV converters. These activities will be expanded on when this paper is presented at EVS-23.

4. Conclusions

The HEV testing has demonstrated the different ways HEVs are engineered to perform. Some of the HEVs maximize fuel use, while others use HEV components to maximize vehicle performance. The HEVs have been demonstrated to be reliable vehicles with significant battery life. After almost 3 million test miles, only one of the nickel metal hybrid traction batteries failed on its own, and it was replaced under warranty. The AVTA will continue to test new HEV models as these vehicles introduce new batteries, new hardware and subsystems, and new control strategies.

The small sample of PHEVs tested to date has clearly demonstrated the potential of PHEVs to deliver significant petroleum reduction, especially when driven in urban missions that include nightly recharging. However, this industry is in its infancy and much is unknown regarding battery fade and life, as well as future economics of conversion costs. In addition to the current conversion companies, there appears to be at least several more announced PHEV conversion companies to come. Several original equipment vehicle manufacturers have also announced future PHEV products; however, there are only very limited numbers of PHEVs on roadways. The AVTA will continue to acquire PHEV models for testing as they become available, in order to provide data to vehicle modelers, developers, and target setters, as well as fleet managers.

5. References

[1] HEV specifications and testing procedures can be found at http://avt.inel.gov/hev.shtml.

[2] All AVTA HEV results, reports, and fact sheets can be found at http://avt.inel.gov/hev.shtml.

[3] HEV fleet test procedures can be found at http://avt.inl.gov/pdf/hev/fep_001_r0.pdf.

[4] D. Karner, R. Brayer, D. Peterson, M. Kirkpatrick, and J. Francfort. *Plug-in Hybrid Electric Vehicle (PHEV) Integrated Test Plan and Evaluation Program (Draft).* INL/EXT-01-12335. Idaho National Laboratory. Idaho Falls, Idaho. July 2007.

[5] All AVTA PHEV results, reports, and fact sheets can be found at http://avt.inel.gov/phev.shtml.

6. Authors

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